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A Review of Artificial Intelligence Techniques as Applied to Adaptive Autoreclosure, with Particular Reference to Deployment with Wind generation

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Abstract - This paper presents a survey of artificial intelligence techniques that have hitherto been applied to adaptive autoreclosure, namely artificial neural networks, fuzzy logic and genetic algorithms. The aim is to discern the most suitable techniques for applying adaptive autoreclosure to systems with high penetrations of wind power. Traditionally, adaptive autoreclosure schemes have been implemented using a combination of signal processing and artificial neural networks. A number of variations on this conventional approach are proposed in this paper. Qualitative discussion shows that in theory, a combination of the examined AI techniques will provide the most robust methodology, combining the strengths of each technique whilst minimizing weaknesses.

Index Terms — Adaptive Autoreclosure, Power System Protection, Artificial Intelligence, Artificial Neural Networks, genetic algorithms

List of abbreviations

AA = Adaptive Autoreclosure

SPG = Single Phase to Ground Fault

DAR = Delayed Autoreclosure

GA = Genetic Algorithms

IED = Intelligent Electronic Device

DFIG = doubly fed induction generator

WAMS = Wide Area Management System

I. INTRODUCTION

Adaptive autoreclosure is the relay facility whereby the faulted current and voltage waveforms are used to diagnose the most appropriate reclose action and time. It is well accepted that in future power systems, fast numerical relays will play an important role in preserving security of supply. The drive to meet increasingly ambitious renewable generation targets will lead to more distributed generation, and grids must evolve to accommodate this greater complexity with real time changes in topology due to the intermittent nature of wind. This imminent revolution in power systems is loosely referred to as 'smart grids'. In addition, the need to meet growing demand, coupled with delays in building new lines, will result in decreased transient stability margins as operators push more power through the

existing infrastructure. Adaptive autoreclosure (AA) would be a valuable facility in stressed future scenarios, minimizing transient fault clearance times, optimizing stability and preventing unnecessary shocks to generator shafts.

As members of the Supergen flexnet research consortium, the authors are developing an adaptive autoreclosure scheme to cope with increased permeation of wind power in distribution networks. The scheme will form part of a numerical unit-based protection relay for overhead lines.

Furthermore, autoreclose algorithms developed will be implemented within the coordinated Wide Area Management scheme [1] developed under flexnet at Strathclyde university.

Work completed so far [2] has demonstrated the transients introduced by power electronics in modern wind turbines, in particular the DFIG generator due to its complex control circuitry, will affect the frequencies used in adaptive autoreclosure schemes. This study highlights the need for robust diagnostic techniques for autoreclosing overhead lines connecting wind generating technology.

II. ADAPTIVE AUTORECLOSURE

Adaptive Autoreclosing (AA) schemes must discern the soonest time it is safe to reenergize a line without incurring secondary trips. Essentially this involves observing the extinguishing of the secondary arc in the case of a transient fault. A permanent fault, such as that caused by a downed line or a tree, will involve a constant fault resistance. A lightning strike or similar event leading to discharge to ground or between phases will be cleared by de-energising the faulted phase(s), (or all three phases should the circuit breaker not allow single pole reclosing). Such transient faults exhibit arcing phenomena, with the fault current flowing to ground through an electrical arc, usually between the arcing horns on a transmission tower. In this case, the fault resistance varies with time in accordance with the behavior of an electric arc. In the first instance, an AA scheme must make the distinction between a transient and a permanent fault through the presence of the arcing phenomena. If a permanent fault is diagnosed, reclosing must be blocked. In the case of a transient fault, the scheme must determine when it is safe to reclose. As outlined in [3] there is a short period after arcing has extinguished when reclosure will simply lead to further arcing. This is partly due to how the secondary arc re-strike

voltage interacts with the line voltage, and also in low wind conditions failure of the ionized arc products to clear can encourage re-striking over the original arcing path.

Over 70% of overhead line faults are single phase to ground (SPG) faults [4]. Circuit breakers that are capable of single pole opening will take advantage of this prevalence in fault types, and only de-energise one phase, thus preserving some of the power transfer through the line. Of course, this mode of operation can only occur for a few seconds since the unbalanced condition will lead to instability elsewhere in the system. Any AA scheme is heavily dependent on the type of circuit breakers employed since post fault information is required to assess the ongoing suitability of a reclosure decision. Therefore most adaptive autoreclosure schemes rely on secondary arcing that occurs after the faulted phase is opened, caused and sustained by coupling between the healthy and faulted phases. Three phase AA schemes have been proposed [5] for double circuit lines that use secondary arcs caused by inter *circuit* coupling.

In the UK, the vast majority of circuit breakers are three phase only. Thus AA schemes deployed on the current UK system must be designed accordingly. However, ageing infrastructure represents an opportunity to upgrade to single pole circuit breakers should this prove cost effective. Furthermore, much of the infrastructure connecting windfarms is yet to be built. The remote location of new substations will require a design emphasis on greater automation of secondary system and high and exposed overhead lines are more prone to transient faults caused by adverse weather conditions.

A further consideration is the effect of any reclosure decision on transient stability. A reclose operation causes a large step change in the configuration of the network, which follows the initial fault, also a large disturbance. It is thus important that any reclose operation be assessed from a stability point of view before it can be allowed. Moreover, the mismatching between mechanical power and electrical power can lead to extra stresses on generator components as the change in power flow is accommodated by rotor acceleration. Most modern turbines use power electronics to a greater or lesser extent in combination with induction generators so conventional treatments of transient synchronous stability are not valid. In this case stability is meant in the sense that wind turbines can tolerate grid faults without overspeeding. Results in [2] also suggest there is an upper limit to the length of time a full inverter turbine can remain in two phase operation.

With these considerations in mind, an adaptive autoreclosure facility must have the following abilities:

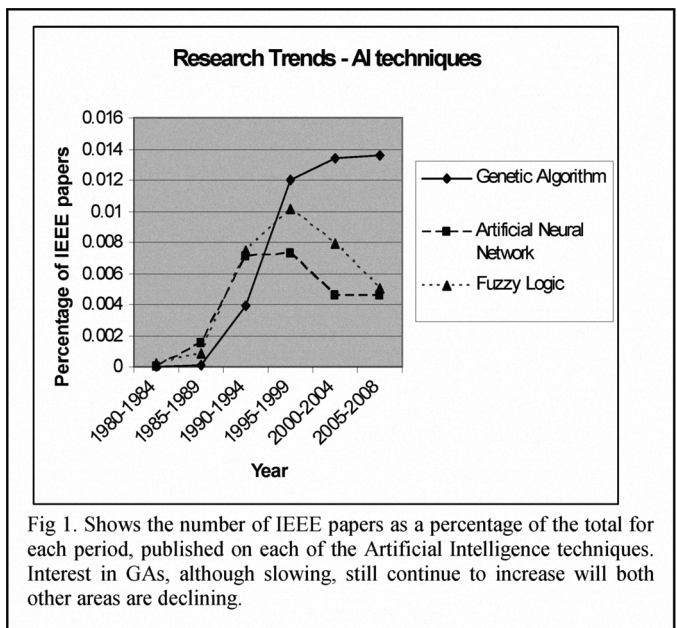
- It must not jeopardize stability or local generation through sudden changes in network topology
 - The worst case reclosure decision must present no more threat to the integrity of the power system than a conventional DAR scheme.
- If single pole tripping is employed, it must first be able to diagnose the faulted phase
 - It must distinguish between permanent and transient faults
 - In the case of a transient fault, it must determine the safe autoreclosure time
 - It must be able to reach a decision in real time

III. ARTIFICIAL INTELLIGENCE

Artificial intelligence is a branch of computer science that attempts to use examples in nature to solve problems that conventional computing techniques find problematic. Inspiration is drawn from a range of sources from human reasoning, natural selection in evolution and the physical topology of the brain. They share common qualities in that they are robust, highly-parallel, can deal with incomplete data, and perform well in extrapolating non-linearity. Escalation in complexity in power systems lends itself to problems to which artificial intelligence are well suited; examples include load forecasting, reactive power control, protection and alarm systems [6]. The complex interplay of variables that ultimately influence a reclose decision in adaptive autoreclosure is one specific area where AI techniques have been successfully applied.

IV. ARTIFICIAL NEURAL NETWORKS

A particular branch of AI is the Artificial Neural Network (ANN). An ANN comprises of a number of small processing components wired together, in a much simplified topology of the neurons and synaptic pathways in the brain. The processing components work in parallel increasing the speed of the device and tolerance to failure, in that a loss of a single processing unit will not significantly affect the functioning of the device. The synaptic pathways each have an associated weighting function and the neurons a firing function, known



as the transfer function. When the inputs to the neuron reach a level defined by the transfer function, the signal is transferred across to the next layer in the architecture. The weights must be adjusted to give the desired output for a given input. This process is known as training. Neural networks must be trained with data with a known outcome, in order to reach the desired outcome for unknown data. In practice this means that ANN based AA schemes must be subjected to a considerable number of fault cases before they can produce the correct output. The system under consideration must be simulated for a number of fault conditions offline before confidence in the ANN's performance can be assured. It is for this reason that such schemes in the past have been confined to bespoke solutions to a particular location on the network.

ANNs have been applied to AA schemes with some success. In particular, the Multi-Layer-Perceptron architecture has seen promising application in the past in [7] and [8]. However, using the raw time series data is impossible due to the many other power system characteristics that pollute the signal at a range of frequencies. The signatures benefit from processing in some way, so that through training, the ANN can weight the importance of contributions of different frequencies. Often preprocessing is achieved by transforming the signal into the frequency domain, whilst retaining information where these crucial frequencies occur in the time domain. This can be achieved by the windowed FFT [8] and discrete wavelet transform [9].

Recent work on the transient response of windfarms [2] has validated the neuro-wavelet approach. This is because the fault conditions are shown to have a greater influence on the fault signatures than the generating technology. However, more work needs to be done on stability, and how the control system and design of the generating units in the wind influence this. If single pole operation proves unfeasible then perhaps the intercircuit coupling approach in [4] would be prudent.

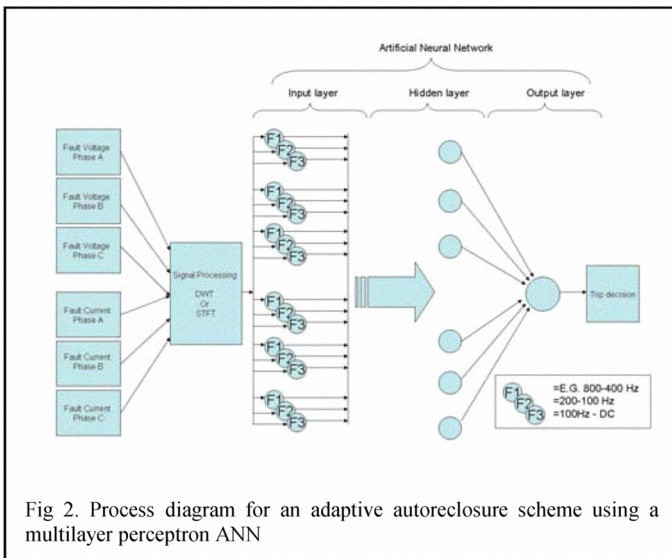


Fig 2. Process diagram for an adaptive autoreclosure scheme using a multilayer perceptron ANN

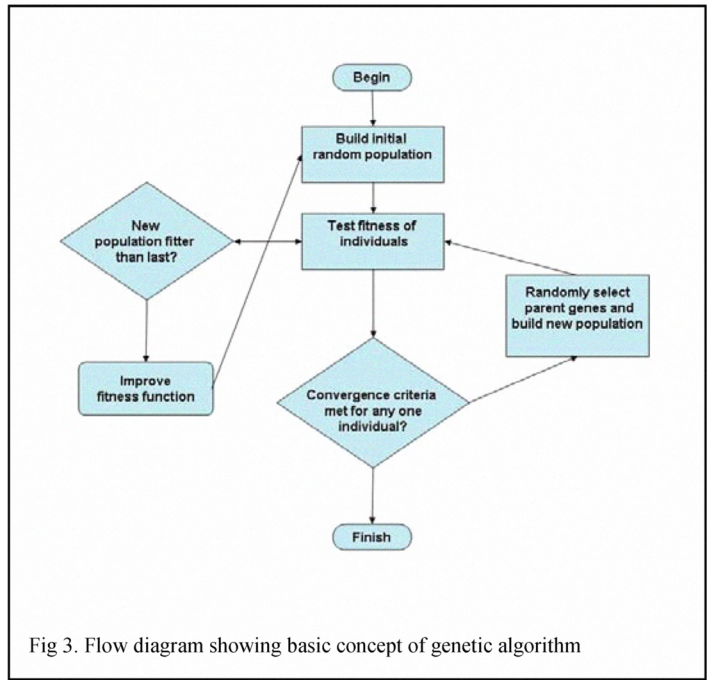


Fig 3. Flow diagram showing basic concept of genetic algorithm

V. GENETIC ALGORITHMS

Genetic Algorithms (GAs) are a subgroup of evolutionary computing along with genetic programming, classifier systems and simulated annealing. However, GAs are the most widely developed - they are behind over 95% of papers published in evolutionary computing [10]. Genetic Algorithms are a parallel search and optimization technique based on the mechanisms involved in evolution in nature. Their success is down to their simplicity and versatility concept. Figure 1 shows that their interest in the research community is continuing to increase. Genetic algorithms can be applied in a multitude of different ways, but are very useful for exploring a multidimensional search space whose dimensions are non-linear and non-differentiable. A genetic algorithm involves the same basic pattern:

1. Initially, a population of individuals, which each represent solutions to a given problem, is generated at random. The individuals, called chromosomes or genomes, are represented by "genes" that are elements to a solution. Each gene is usually encoded as a binary string.
2. These solutions are individually tested for their ability to solve the problem. They are then assigned a fitness based on this ability.
3. Two individuals are chosen at random to reproduce. This selection is weighted depending on the fitness score, so fitter individuals are more likely to be selected. The method used is thus often known as "roulette wheel" selection since it conceptually resembles a roulette wheel whose segments are different sizes.
4. The parents of the new individuals "reproduce" by each contributing some of their genes to the offspring. Crossover determines the amount of genes that each

individual supplies – usually the point in the genome where the parent genes are cut, and mutation represents the chance of a gene replicating error in the reproduction process. Offspring are then decoded and their fitness functions evaluated.

5. This process is repeated a number of times (successive generations) until a satisfactory solution is reached, i.e. an individual with a high enough fitness function is produced.

In addition to the processes described above, the fittest individuals can be cloned and included in subsequent generations in a process known as elitism. In some cases, the algorithm can improve the effect of the fitness function by assessing the new population's fitness against that of the previous generation. If the population does not improve, the fitness criteria can be made more rigorous. This mimics the predator-prey 'arms races' that occur in nature, where an advantageous change in the predator will stimulate a corresponding improvement in their prey.

The potential uses of genetic algorithms are wide ranging. However, their successful implementation depends heavily on defining and measuring the fitness function. Other critical factors are the length of the genome, population size, number of generations and the selection and encoding of the elements of the solution i.e. the genes. As such, algorithms in practice often require a good deal of 'tweaking' to maximize their efficacy.

In adaptive autoreclosure it is difficult to frame the reclose decision as a search problem because the full fault signature is not available. Also GAs require a large number of operations so are relatively computationally expensive, with long implementation times, even for modern processors. For these reasons, their use is generally confined to offline.

However, they have been used in the past to assist the training of MLP neural networks, and are shown to be more efficient than the standard back - propagation method [11].

Arguably the most important role of power system protection at transmission level is preserving stability. As mentioned before, the autoreclose scheme represents a large disturbance following an initial disturbance of the fault itself. Careful attention must therefore be paid to stability in any AA scheme. Transient stability margins in the UK are based on the interplay between tripping time following a fault, and the maximum power that can be transmitted without jeopardising synchronism should such a fault occur. Better clearance times allow greater power transfer. Calculations are often based on the assumption that stability is lost on the first power swing, but with fast reclose a second disturbance could also pose a threat to the system [4]. Safe reclose time depends on a whole array of variables depending on the local generation and network topology surrounding line on which it is deployed. This is further complicated with wind generation due to wind variation, asynchronous generators and power electronic converters. A genetic algorithm could be best used offline to generate a range of stable autoreclose sequences.

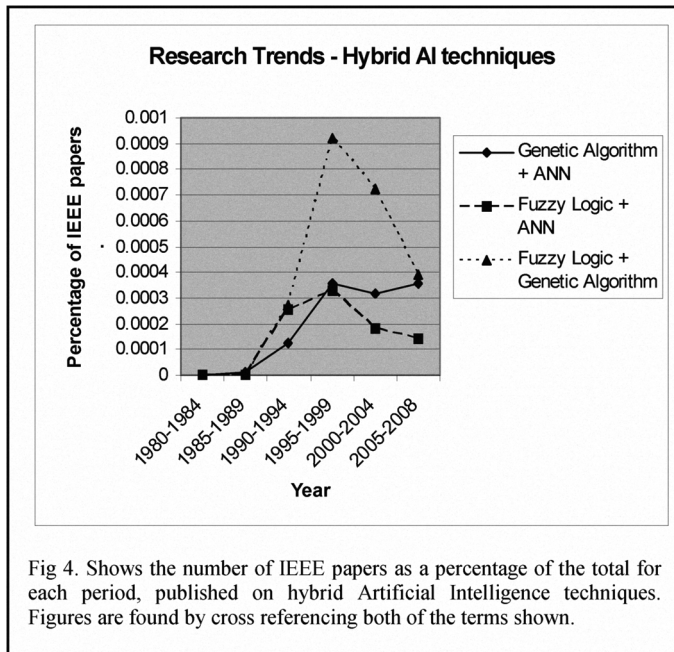
VI. FUZZY LOGIC

Fuzzy logic, in the broadest sense, is a system of logic where elements occupy classes with boundaries that are not sharply defined [12]. It is often used in the form of expert systems, which rely on a series of IF-THEN-ELSE rules provided by expert knowledge to arrive at a decision. Fuzzy rule sets greatly enhance the performance of expert systems because degree of adherence to class allows built in confidence values rather than only allowing a variable to take on Boolean values. Similar to some ANN architectures, fuzzy logic rules can be used to map inputs onto nonlinear outputs. Unlike ANNs however, no training is required for calibration and the rules underpinning the networks are easy and intuitive to understand. Determining of the fuzzy rule sets can be achieved by the experience of a human expert rather than direct data relating to the problem at hand. In addition, rules can be added at a later stage without the need to rewrite existing rule sets. With an adaptive autoreclose facility this would mitigate the need for extensive simulation studies offline. It could also allow IEDs to be updated via remote link when improved fault data becomes available, or a user to extend the rule set manually should the system topology be altered with new plant.

The elements in the system are often defined with linguistic values rather than numeric variables. Although less precise, this emulates the uncertainty often inherent in real world problems and is more intuitive for humans. In fact, fuzzy logic is directly analogous to the way the human brain interprets language. Unlike conventional computing methods, where precision usually takes precedence over significance, fuzzy systems are able to manage this trade-off effectively. [6] In a fuzzy inference system, sometimes only rough estimates of some quantities are required. Thus fuzzy logic lends itself to online calculations as computational expense is minimised.

In the past, fuzzy logic has often been applied in a hybrid system in conjunction with Neural networks [13] for the important task of phase diagnosis in single pole reclosure. This can be achieved in 10ms and so is effective as an online technique. Such a facility is a pre-requisite for any AA scheme based on single pole reclosing.

Moving towards commercial deployment, user installation of Adaptive Autoreclosing IEDs could potentially be improved by fuzzy logic. In such a scheme the user inputs data about the local primary system. A series of desired outcomes could be set based on the system – together with the 'worse case' limits as boundaries. For example, one such limiting rule could be "at all costs, an unsuccessful reclose operation should be avoided". Such inflexibility might not achieve optimal reclose times, but would nonetheless greatly improve them without the need for lengthy simulation and validation studies on the exact system configuration. A fuzzy scheme may also prove useful in selecting a pseudo-adaptive sequence, by applying human judgment in microseconds.



VII. HYBRID AI SYSTEMS

In the past hybrid AA schemes have overcome some of the shortcomings presented by individual techniques. For example training of ANNs have been achieved with genetic algorithms [11]. Also recent work on the transient response of wind farms has validated the neuro-wavelet approach. Designing a practical AA scheme presents a series of challenges that are suited to different AI approaches.

For example, Fuzzy Logic rule sets can help in the installation of and calibration of IED by control engineers, who harness expertise on local network through providing a series of IF-THEN rules. (Also these may be easily updated at a later stage as knowledge is accumulated). As discussed previously, the complex interplay of variables that affect windfarm stability can be dealt with by genetic algorithms.

The exponential growth in microprocessor speeds and their decrease in costs in recent years gives feasibility to a scheme where a number of AI methods are employed in parallel. This would give a confidence value in any reclose decision issued, calculated on basis of level of agreement between different methods. Should the confidence value fall below a certain level, the reclose decision would default to a failsafe condition. Perhaps safest practice would be to run many algorithms in parallel and select the 'pre-programmed' sequence that the majority of the algorithms select; a kind of super-parallel "meta-neural-net".

It is hoped that in future the Distributed Protection Architecture (DPA), part of the WAMS system, under development at the university of Strathclyde [1] could incorporate adaptive autoreclose. It is also likely that AI techniques such as those discussed here will be implemented in the supervisory and management layers, AI scheme. With

this approach an adaptive autoreclose action could be made with confidence in optimal system-wide consequences.

VIII. CONCLUSION

This paper represents a discussion of the considerations involved in adaptive autoreclosure schemes, and how AI methods have been used in the existing literature, as well as offering suggestions for future implementation.

Clearly each of the AI techniques discussed are suited to different applications. For this reason, a hybridisation of AI techniques is likely to build in greater robustness for future adaptive autoreclosure techniques.

Robustness is particularly important with lines near to wind generation. Due to the more complex control circuitry reclose decisions must take into account stability assessment along with restoration of supply.

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